A STUDY ON THE CONDUCTIVITY OF THE NERVOUS SYSTEM.[1]

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Recently the anatomy and the histology of the nervous system have been much studied, while its physiology is as yet very little known. We are specially ignorant of the nature of nervous conduction. Many years ago certain scientists tried to identify it with electricity, but after some experimental study it was found out that there were three points of disagreement between the two, viz.: (1). The velocity of nervous conduction was much slower than that of an electric current; (2). The nerve fibers were not insulated as an electric wire is; and (3). The nervous conduction did not produce an induction current as an electric current does. These scientists, therefore, came to the conclusion that nervous conduction was a result of some chemical change peculiar to nerve fibers. They were forced to do so for the reason that they could not think of any other explanation. Our desire for scientific knowledge will not be satisfied until the details of the chemical changes accompanying the nervous conduction have been made plain. The physiology of nervous conduction is in its present state very imperfect. It is, however, impossible for us to study psychology without some knowledge of the physiology of the nerves. Such was the motive

[1] The following investigations have been pursued under the great disadvantage of having at my disposal only a limited number of books and magazines available for reference. It must, however, be gratefully acknowledged that several of the professors in the University and some others have generously furnished me with valuable help and suggestions, without which it would have been hardly possible for me to attain to any degree of success, as the subject is related in different ways to so many sciences other than psychology itself. My thanks are specially due to Dr. I. Miyake for aid in the measurement of velocity, and to Profs. G. Yamakawa, K. Osawa and K. Ikeda for furnishing me with many necessary points on electricity, the physiology of the nerves, and thermo-electricity.

which led me to the investigation of this problem; and though I do not claim to have succeeded in solving it, yet I hope the results given in the following paragraphs may give some clue to its satisfactory solution in the future.

About seven or eight years ago, it occurred to me that the nervous conduction might possibly be the transmission of a wave produced in a liquid contained in the nerve fiber. I then took a rubber tube nearly 20 feet long, and filled it with water to see the manner of transmission of the water wave. I struck one end of it, and the wave was transmitted very distinctly to the other end. I measured its velocity, and found that it was nearly 100 feet per second. Although the method of measuring was very imperfect, the velocity of the wave coincided so nearly with that of nervous transmission that I was induced to pursue the investigation further. But being unable to find any other point of analogy, I left the problem as hopeless, and did not take it up again for the next six or seven years.

In the spring of last year, this problem came again to my mind. I wondered whether we could not produce an action current in a rubber tube filled with water, and whether we could not produce inhibition in the tube. I made some apparatus specially for this purpose, and experimented on these points. The results obtained, though they differed somewhat from those I expected, were on the whole very satisfactory. I shall first describe the experiments made, then give their interpretation, and lastly compare the results with nervous conduction.

First Experiment.

The aim of this experiment was to measure the velocity of transmission of a wave in a rubber tube.

The apparatus used for this purpose is shown in Fig. 1. In the first place, it is so arranged as to move the recorder *K* of Fig. 2. which forms a part of *H* in Fig. 1. The recorder is moved first when one end of the rubber tube *A* in Fig. 1. is touched, and secondly when a wave reaches the other end. One end of the rubber tube is fitted to a kind of tambour *B*, the other end to the U-shaped glass tube *I*, which is partly filled with mercury. *F* is a rod of ebonite at one end of which is a metallic button which is connected with the wire *G* by

FIG. 1.

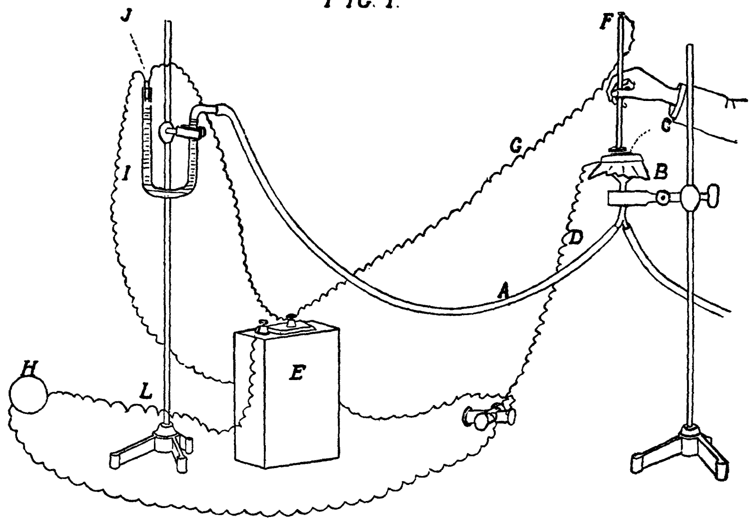
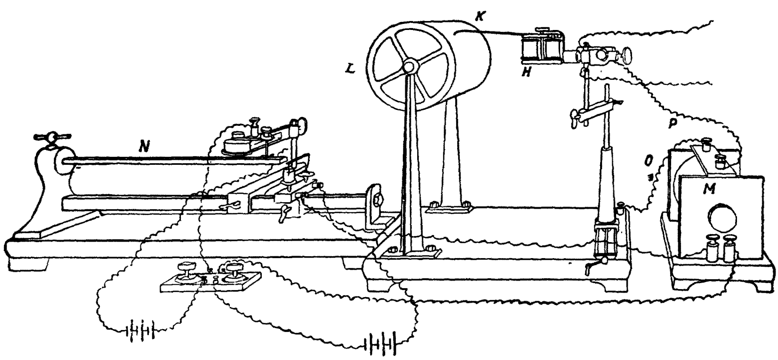


FIG. 2.



means of another wire passing through the interior of the rod and terminating at the other end. Thus a series consisting of a button and pieces of wire is connected with the battery *E*. *C* is a small piece of metallic plate which is connected with the other pole of the battery *E* through the wire *D*, the electro-magnet *H*, and the wire *L*. When the button touches *C* the circuit is closed, but is immediately opened again by lifting the button. By this closure, the recorder *K* in Fig. 2 is moved and a small curve is left recorded as shown in Fig. 3. When

the wave reaches the other end of the tube, the mercury in the glass tube rises and touches *J*, a piece of insulating material holding together the ends of two wires. Thus the second circuit is made, which moves the recorder for the second time.

Secondly, there is an arrangement for recording time by means of a series of spots on a straight line. The apparatus is shown in Fig. 2. *H* is an electro-magnet connected with the recorder *K*, corresponding to *H* in Fig. 1. *L* is a drum covered with smoked paper. *M* is an induction coil, the secondary current of which is connected with the recorder by means of wire *P* on the one hand, and with the drum by means of wire *O* and the stand supporting the drum on the other. Thus, when an interrupted primary current passes through the coil, a spark is produced between the recorder and the drum, which leaves a white spot on the smoked paper. This is Prof. Scripture's method of recording time. *N* is the interrupter of the primary current, devised by Prof. M. Matsumoto. This apparatus may be adjusted to interrupt any number of times in a second. In this experiment it interrupted fifty times a second. The interval between the spots on the record shown in Fig. 3, represents one fiftieth of a second. In this record of Fig. 3, we have 39.7 of such intervals between the first and the second contact. By changing the unit from one fiftieth to one hundredth of a second, Σ, the above number becomes 79.4 Σ.

Thirdly, we have to eliminate an error which comes from the inertia of the mercury. For this purpose I used a tube of a certain length, and then used another of just half that length. Representing by X the latent time produced by the inertia, by a the time for the transmission of the wave through the rubber tube, and by C the time including both of them, from the first experiment we have the equation

$$a + X = C \quad (1).$$

From the second experiment we have the equation

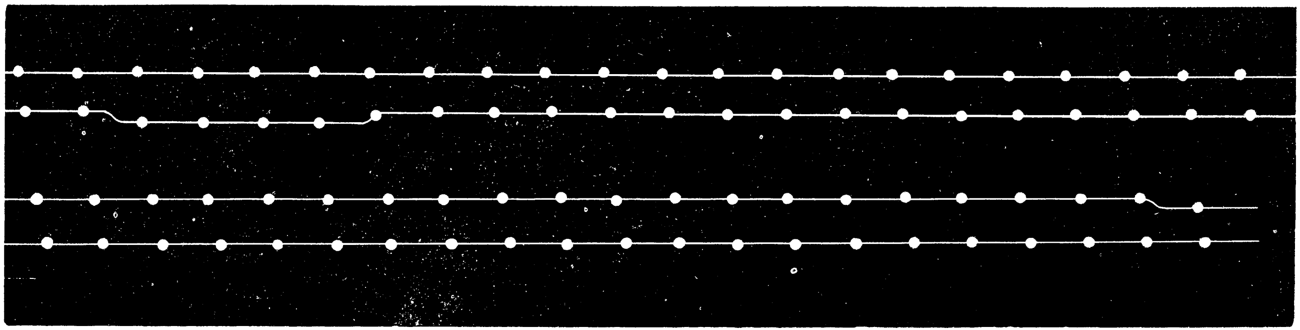
$$\tfrac{1}{2}a + X = C' \quad (2).$$

From the two equations we can find the value of X:—

$$X = 2C' - C.$$

Thus I obtained the value 3.36 for the latent time in this experiment.

FIG. 3.



Fourthly, we shall show the results thus obtained, in the following tables:—

TABLE I.

Showing the velocity of wave transmission in different kinds of rubber tubes.

Kind of the tube.	Inner diameter in mm.	Length in m.	Time in seconds.	Mean variation.	Meters. per second.
Black tube.	6.	9.66	.796	.013	13.40
Do. (a little harder).	6.	6.53	.54	.9175	13.92
Do.	4.	6.66	.4488	.0105	16.21
White rubber tube.	6.0	1.85	.108	.0012	26.87
Do.	2.8	6.66	.0938	.0026	67.00

TABLE II.

Showing the influence of change of pressure, using the black tube.

Pressure Merc. Col. in cm.	Diameter in mm.	Length in m.	Time in seconds.	Mean variation.	Meters per second.
No pres.	6.	9.66	.8324	.01612	12.66
10.6	6.	9.66	.7692	.00896	13.76
16.75	6.	9.66	.7992	.00864	13.33
−9.00	6.	9.66	.8012	.00944	13.16

TABLE III.

Showing the influence of change of temperature, using the black tube.

Temperature in C.	Diameter.	Length.	Time.	M. V.	Velocity
Tem. of room	6.	9.66	.743	.0046	14.30
90	6.	9.66	.811	.005	13.00

TABLE IV.

Showing the influence of strength of stimulus, using the black tube.

Strength.	Diameter.	Length.	Time.	M. V.	Velocity.
Weak	6.	9.66	.796	.013	13.09
Strong	6.	9.66	.796	.0091	13.03

From these tables we learn the following points:

(1). That the velocity of the wave varies according to the nature of the rubber; and that it increases with the elasticity of the rubber, for we know that a white tube has greater elasticity than a black one, and a tube of smaller diameter than one of larger diameter.

(2). That the velocity increases with pressure up to a certain point, beyond which it decreases as pressure increases.

(3). That the velocity decreases as temperature increases.

(4). That the velocity is independent of the strength of stimulus, for the difference in our results is so small that we may consider it as probable error.

Interpretation.

The law of propagation of a wave in a liquid is as yet very little studied. It is conditioned by so many circumstances that it is very difficult to take them all into consideration. Prof. Maxwell gives us the following formula:

$$U^2 = EV$$

Where U is the velocity, E is the elasticity, and V is the volume of the unit mass (J. Clark Maxwell, Theory of Heat, p. 207). Moens gives us a more exact form of it in the following formula:

$$Vp = 0.9\sqrt{\frac{gEa}{\triangle d}}$$

where E is the elasticity coefficient of the tube in grams per cub. cm., a is the thickness of the tube, d the diameter of the tube in cm., and $\triangle$ the weight of one cub. cm. of the liquid in grams (L. Hermann, Handbuch der Physiologie, IV B., 1ter Theil, S. 221). By comparing these formulæ, we see that, though they differ in their forms and one is more exact than the other, they agree in their essence. In Maxwell's formula, the square of the velocity is proportional to the elasticity and the volume of unit mass; while in Moens' it is proportional to the square root of the elasticity and inversely proportional to the square root of weight of unit volume; this is the same in its meaning as that of Maxwell, and has more conditions besides. Moens found by this formula and experiment that the velocity of wave propagation comes between 12 and 16 meters per second, with different intensities of pressure, and with different a and d. This result agrees with ours, except those obtained with the white tube, which is much harder than the black one. But Moens' formula agrees in approximation with our result in this, that the white tube, which has more elasticity and thickness, transmits the wave more quickly than does the black one, and that in comparing the white tubes, the one that has more elasticity and smaller diameter transmits it more quickly.

However, for some unknown reason, the smaller one transmits it a little more rapidly than the formula requires. There is another point which requires notice. In the experiment of Moens and Weber, a strong impression is transmitted more rapidly than is a weak one, while in our experiment a difference of intensity does not make any difference in the velocity of transmission. Probably in our experiment the difference of intensity was not enough to produce a difference in the velocity. Owing to the nature of our apparatus it could not be made greater.

Comparison of our Results with Nervous Conduction.

The velocity of nervous conduction was first measured by Helmholtz. It varies in different kinds of nerves, and the same nerve under different circumstances, *e. g.*, temperature. It ranges somewhere between 27 and 34 m. per sec. (Biedermann, Electro-Physiology, Engl. trans, Vol. 2, p. 60). Sometimes it is as quick as 90 m. (Hermann, Handbuch der Physiologie, B II., S. 23), and in some animals it ranges between 400 mm. and 1 m. (Biedermann, *op. cit.*, p. 61.) Thus we see that the range of the variation of velocity may come within that of the variation of velocity in the rubber tubes. In regard to the influence of pressure, I have nothing to say. As to temperature, my experiment showed a tendency opposite to that in the nerve. In my experiment the velocity decreased as temperature increased, while in the nerve it increases. Probably in the nerve the elasticity of protoplasm increases, while in the rubber tube the elasticity decreases, as temperature increases. Here the analogy fails, for one is living matter while the other is inanimate matter. Lastly, there is a disagreement of opinion among authorities as to whether the velocity of nervous conduction increases with the intensity of the stimulus. After all, the experiments of scientists seem to favor an answer in the affirmative. In my experiment, I could not find an influence of intensity, but in Moens' experiment there is such an influence. Thus the analogy between the nervous conduction and wave transmission may be retained here.

These facts, however, do not exclude the possibility of the

chemical explanation. For a certain chemical change such as crystallization of phosphorus is said to proceed with the velocity of 1 m. per second, while the explosion of dynamite goes several times faster than nervous conduction. Some chemical changes may proceed with just the same velocity as nervous conduction. It may be a kind of combustion, or a change in molecular arrangement. Or it may be a wave of protoplasmic contraction. It may perhaps be a combination of protoplasmic contraction and water wave. Finally, the analogy of velocity does not prove any thing definitely, for so many things have nearly the same velocity. This proves, however, that the nervous conduction may be explained on the hydraulic principle, if other analogies point toward the same conclusion.

SECOND EXPERIMENT.

The aim of this experiment was to see whether we could produce the so-called action current in a rubber tube filled with slightly acidulated water.

(a). For this purpose I made such an arrangement as is shown in Fig. 4. The general plan is the same as it is in Fig. 1. *B* and *C* are tubes of ebonite to which three rubber tubes are fitted to form one connected tube as in the figure, and they are connected with a galvanometer by wires. Thus we have a circuit completed, including the galvanometer and the liquid in a part of the tube. I noticed that a current existed, probably owing to the action of the acidulated water on the metal screwed on the ebonite. I noticed a striking change in the electric state when a stroke was given at one end of the rubber tube. This experiment did not give me anything new, but a suggestion for the next experiment.

(b). I tried to avoid the movement of the water at the point where it touched the metal. I made the arrangement shown in Fig. 5. *A* and *B* represent pieces of zinc plate which were held in position by clamps, and which touched, at their lower ends, acidulated water in the tubes *C* and *D*. At the bottom of the tubes, pieces of cotton were put in to prevent the wave from coming upward. By this arrangement, however, I not only failed to accomplish the end, but added a new disturbing cause, an electric current caused by capillary action in the cotton.

FIG. 4.

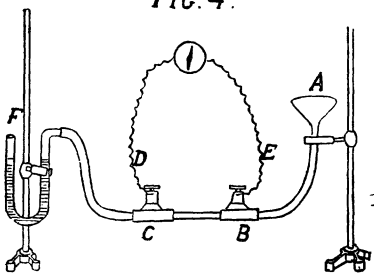
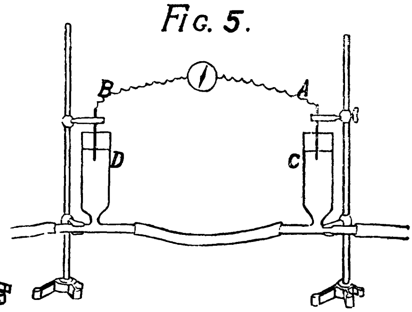


FIG. 5.



(c). Prof. Yamakawa, of the Electrical Engineering Department, suggested that a chemical change might occur between rubber and water. Therefore I substituted a glass tube for the rubber one, lying between *C* and *D* in Fig. 5; took the cotton from the bottom of the tubes; and, finally, substituted platinum for zinc. By this arrangement, I found that there was no electrical disturbance when a wave passed through the horizontal part of the tube. The question immediately suggested was, "What was the cause of the disturbance in the previous experiment?"

(d). In the arrangement of the experiment (c), I again inserted the cotton in *C* and *D*, and noticed that a current was produced when a wave passed through. Thus I was certain that the cotton was a cause of disturbance.

(e). Next I took off the cotton, and coated the inside of the glass tube lying between *C* and *D* with a mixture of ash and shellac, to give friction to the wave. I noticed an electric current when a wave passed through. Thus I came to the conclusion that this current was caused either by friction itself or by the heat thus produced, being a thermo-electric current in the latter case.

(f). I applied heat at the point *C*. I noticed an electric current produced. By applying heat at the point *D*, I noticed a current in an opposite direction. Thus I confirmed my impression that a thermo-electric current existed between the platinum and water. But it is another question whether heat enough for an electric current is produced in a rubber tube, when a wave passes through it.

(g). To answer this question I made a thermopile, on the

FIG. 6.

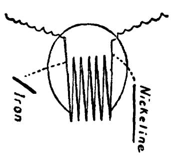


FIG. 7.

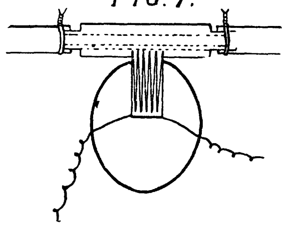
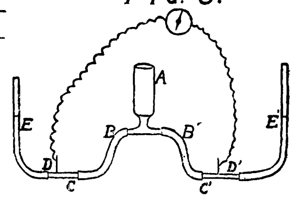


FIG. 8.



suggestion of Prof. Ikeda, of the Chemical Department, by joining together at their ends narrow pieces of iron and nickeline, as is shown in Fig. 6, where the heavy black lines represent iron, and light ones nickeline. The elliptic curve represents sealing wax fixed there to prevent one end from being exposed to changing temperatures. I inserted the other end in a hole made in an ebonite tube lying between the rubber tubes, through which the wave passed, as is shown in Fig. 7. The direct contact of the thermopile with the water was prevented by means of a thin rubber sheet. The terminals of the thermopile were connected with a delicate galvanometer. With this arrangement, I obtained the following readings, 500 being the zero point of the scale.

Before a wave passed through.	After a wave passed.	After a few seconds.
486.0	490.2	479.0
479.0	483.0	480.3
482.5	487.1	482.0
482.0	486.0	482.0
482.0	486.0	480.0
480.0	483.3	480.0

From this table, we see that there were changes of 3.3–6.0 mm., when a wave passed. From another experiment, I found that a deflection of the mirror of 1 mm. amounted nearly to $\frac{1}{250,000}$ of a degree Centigrade.

(h). I tried another experiment to see whether there was not a relation between the direction of the wave and that of the electric current. Fig. 8 shows the general arrangement for this experiment. *A* represents a glass tube whose upper end is opened. *B* and *B'* are rubber tubes. *C* and *C'* are glass tubes whose insides are coated with ash and shellac. *D* and *D'* are wires of platinum which go through the glass and touch the liquid in the tubes. *E* and *E'* are rubber tubes. When a

wave comes from either end, it stops at A. Therefore, a wave coming from the end E stimulates D only, and a wave coming from the end E' stimulates D' only. It made no difference, as to the direction of electric current, whether I struck the rubber tube E to send a wave from E to B, or the tube B to send a wave from B to E. I concluded, therefore, that the direction of the electric current depended upon which electrode was excited, and not upon the direction of the wave.

(i). These results suggested the question whether we could not produce a thermo-electric current in a nerve. To answer this question, I made the following experiment. I took a sciatic nerve of a frog, and applied unpolarizable electrodes at two points somewhat distant from each other. Pouring on hot water at one of the points, I noticed such a deflection of the galvanometer as to show an electric current passing through the galvanometer from the hot to the cold point. Next I used two pins as electrodes, and warmed one of them before applying them to the nerve. I found the same result as before.

I wished to know what would happen, if the nerve itself were warmed instead of an electrode, but I could not succeed in this experiment, owing to the mechanical difficulty of warming a nerve. Therefore I warmed one part of my own body and applied an electrode to it, while the other electrode was applied to the colder part of the body. I found an electric current passing through the galvanometer from the colder part to the warmer part.

(j). Does a nerve produce heat when a stimulus passes through it? To answer this question, I took a sciatic nerve of a middle-sized frog, together with a muscle, and applied the theremopile at a certain point in the nerve, while two electrodes gave a shock at the end of the nerve further from the muscle. In this experiment, one shock gave no deflection in the galvanometer, but when I gave a faradic current continuing half a minute, the mirror was deflected 2 mm.

To make sure that the heat observed at the point adjacent to the thermopile was not the heat transmitted from the point at which the stimulating electrodes were applied, I had put a piece of iron between these points to intercept it. Thus the deflection of the mirror must be entirely attributed to the heat produced at the point next the thermopile.

The galvanometer used in this experiment was a Deprez-d'Arsonval mirror galvanometer, read with a telescope and scale in the usual way. The distance of the telescope from the mirror was nearly 1.5 m enabling me to read a very small deflection of the mirror. The internal resistance of the galvanometer is nearly 400 Ohms, and 8.5×10^{-10} ampere produces a movement of the scale of 1 mm.

Interpretation.

When any two electric conductors are brought in contact, a difference of potential is produced between the two. If we dip the ends not so touched in acidulated water, a current is produced through the water from one to the other. If the conductors be copper and zinc, the current passes from the zinc to the copper through the water and from the copper to the zinc at their points of contact outside. Instead of directly connecting copper with zinc, if we connect them by means of a wire, supposing the temperature to be the same everywhere in the circuit, a current goes from copper to zinc through the wire. If the temperature is raised as, for instance, at the point of contact—a current called a thermo-electric current is produced, whose direction differs according to the nature of the conductors thus connected. Prof. Wiedemann divided all kinds of conductors into two large classes, the first class composed of metallic conductors, and the second of electrolytic conductors. The former produces electricity without any chemical change, and includes metals, a peroxide, and a compound of metal and sulphur. The latter needs chemical decomposition to produce an electric current, and includes in it all kinds of salts in the widest sense of the word, water, and others. (Gustav Wiedemann, Die Lehre von der Electricität, 1ter B., S. 191.)

Mere contact of two conductors produces a difference of potential, but the energy of the current may come from chemical decomposition. Electric currents and chemical changes are very intimately connected, but the connection is not essential. A current may be produced without any chemical change, as is the case with a thermo-electric current. Prof. Balfour Stewart says, "It was discovered by Seebeck that if a circuit composed of two different metals soldered together have one of

its junctions heated, an electric current will be produced." He says again, "If a compound circuit be made with any two metals in the following list, the positive current will go across the heated junction from the metal nearest the top to that nearest the bottom of the list:—

(1) Bismuth	(4) Tin	(7) Silver	(10) Antimony
(2) Nickel	(5) Copper	(8) Zinc	(11) Tellurium."
(3) Lead	(6) Platinum	(9) Iron	

(Balfour Stewart, An Elementary Treatise on Heat, 2nd Ed. pp. 157-58.)

A thermo-electric current is produced not only between matals but between a metal and an electrolyte, and also between electrolytes themselves. Prof. Wiedemann gives the following facts: When two platinum plates connected with a galvanometer, one of which is heated, are dipped in cold water, the heated one becomes positive toward the cold one (compare experiment (i) above). We may have the same result by dipping the two plates first and then pouring hot water on one of them. A hot platinum wire becomes positive toward a cold one in the following liquids:—sulphuric acid, nitric acid, ammoniac, solution of magnesium sulphate, tin chloride, copper chloride, iron chloride, and some other liquids. It becomes negative in the following liquids:—chlorhydric acid, oxalic acid, vinegar, potash, potassium carbonate, and some other liquids—(Gustav Wiedemann, *op. cit.*, 2ter B., S. 30. 304-5). Prof. Wiedemann says, in another place, concerning the thermo-electric current produced between two different electrolytes, that there is a doubt as to whether heat is the direct cause of the current or whether heat produces a chemical change which is the direct cause. And he gives various facts to show that there are many cases in which heating of the point of contact of the two electrolytes produces a current (Wiedemann, *op. cit.*, 2ter B., S. 316-20). And again he says, there is a phenomenon called the electric current of a stream of fluid. When a current of liquid passes through a partition of porous matter, an electric current is produced. And when a liquid flows through a tube, as small as 0.949–0.152 mm. in diameter and 10–55 mm. long, an electric current is produced whose direction coincides with that of the liquid, and whose intensity is nearly proportional to

the difference of pressure, by which the stream of liquid is caused. (Wiedemann, *op. cit.*, 1ter B., S. 982-993.)

By comparing these facts with the experiment (b), we see why the cotton was a cause of electric disturbance. By referring to experiments (e), (f), and (g), we see that there is a certain relation between heat and the electric current, but the fact just described, suggests a doubt as to whether heat was the only cause of the current in these experiments, or whether the current was partly caused by heat and partly caused by the motion of the liquid in the tube. By experiment (h), we see, however, that the direction of the current does not depend on that of the liquid motion, as it must do if the current depends on liquid motion. Hence I am convinced that the electric current in these experiments was a thermo-electric current.

Comparison of our Results with the Electric Current in the Nerve.

We are not certain as to whether there is any current in the nerve when it is in a state of rest, though we know that there is a current in the nerve when an impulse passes through it. This current is called an action current or a negative variation, for the point where the impulse is passing becomes negative toward all the other points. Concerning the nature of this current we have not any definite knowledge, in spite of the attention paid to it by many scientists. The problem, in which the scientists' attention is focused, is whether the action current is essential to nervous activity or not. I do not wish to enter upon a physiological discussion, but I believe that the action current is explicable as a thermo-electric current produced between the two points of the nerve where the two electrodes touch it (compare the experiments (i) and (j)).

THIRD EXPERIMENT.

The purpose of this experiment was to find whether we could produce in a rubber tube a phenomenon similar to inhibition in the nerve. For this purpose I made the arrangement shown in Fig. 9. Fig. 10 is a plan of its most essential part. *A* is a reservoir having a piston to regulate the pressure of water in it. There are six openings, four on the sides of the reservoir itself and two in the piston, to each of which a stopcock is fixed, which may be closed or opened at pleasure. One of

Fig. 9.

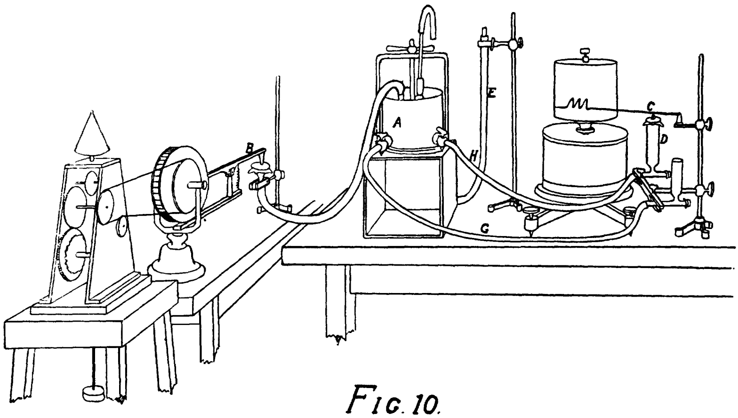
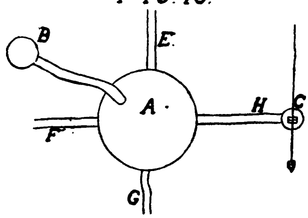


Fig. 10.



these openings is for the pouring in of water. Another is to transmit a wave produced at B to the reservoir by means of a rubber tube. E, F, G and H are rubber tubes which lead the wave away from the reservoir. When E, F, and G are closed, the tube H will lead off the wave. D is a glass tube whose upper end is covered with a thin rubber sheet which moves freely as the water in the tube moves. A small piece of cork on the rubber sheet supports a recorder. When a wave arrives at D, the recorder is moved and leaves a record on the smoked paper. This record is a series of curves with a certain height. When E was opened together with H, the height of the curve was diminished as a part of the wave was lead off by E. When F, which was a little larger than E, was opened, the height of the curve was still more diminished. By measuring the height of each curve, I obtained the following results.

Standard curve.	E. F. G. curves resp'ly.	Differ. or quantity led off.	Diameter of tubes.	Ratio bet. the quant. and the diameter.
12.	8.	4.	9.	2.25
12.	7.	5.	11.5	2.3
12.	5.	7.	16.5	2.35

From this table we see that the quantity of wave led off is nearly proportional to the diameter of the tube.

Next I studied the relation of the wave led off to the length of the tube. By using a tube 1.5 m. long, then one of half its length, then one of one-fourth its length, and finally one of one-eighth its length, I obtained by measurement and calculation the following results.

Standard curve.	Height of each curve.	Difference or quantity led off.	Length of each tube.
11.8	8.5	3.3	1500.
11.8	6.5	5.15	750.
11.8	6.05	5.75	375.
11.8	5.3	6.5	187.5

From this table we see that as the length of the tube decreases the quantity led off increases, but we cannot find any definite law. I may formulate these results in the following propositions:—

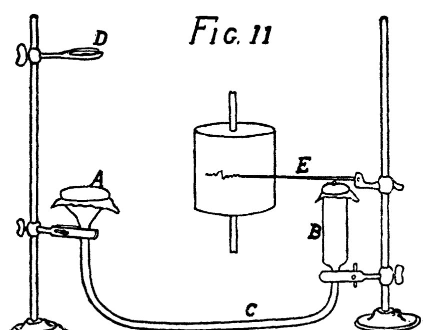
(a). The quantity of the wave led off by any tube is nearly proportional to its diameter.

(b). The quantity of the wave led off by any tube increases as its length decreases.

Fourth Experiment.

I tried to see how sensitive was the transmission of a wave by a rubber tube. For this purpose I made the arrangement shown in Fig. 11. *A* is a funnel whose upper end is covered

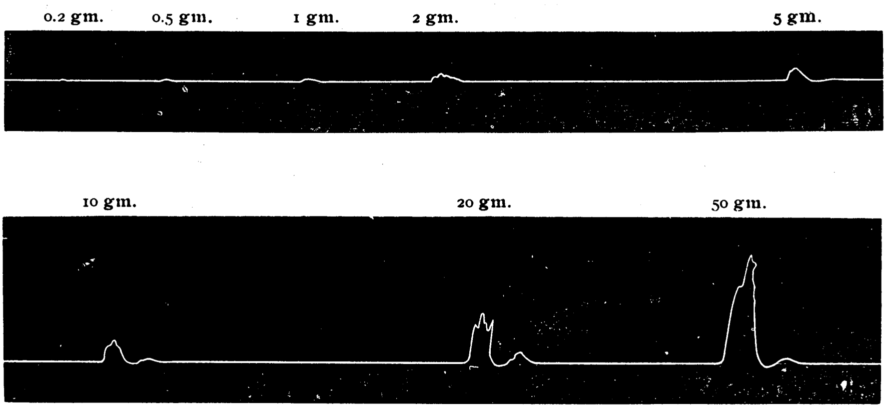
Fig. 11



with a rubber sheet, while its lower end is connected with the rubber tube *C*, which is connected at the other end with the glass tube *B*. Different weights dropped from *D* on *A*, pro-

Fig. 11a.

Using a Rubber Tube whose diameter was 6 mm.



Using a Rubber Tube whose diameter was 9 mm.

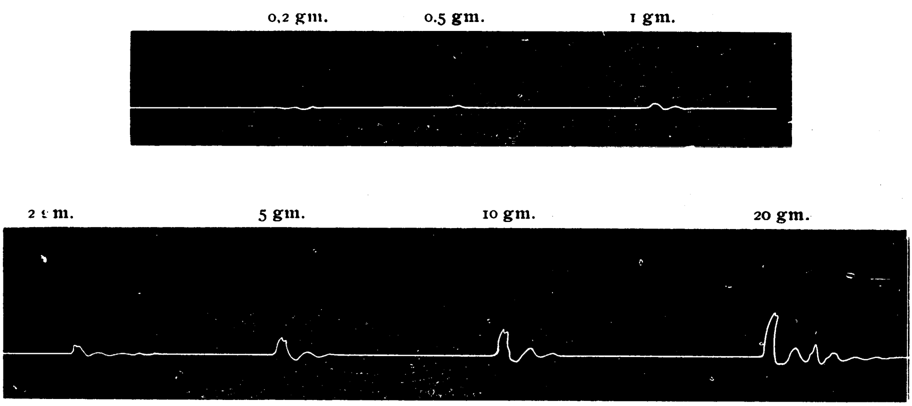
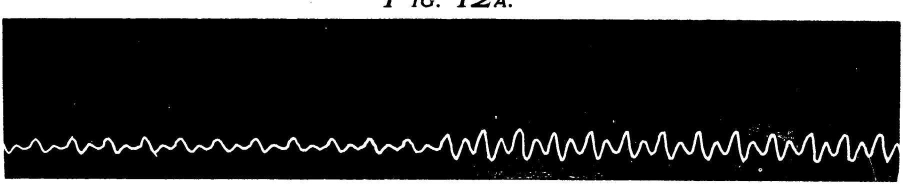


Fig. 12a.



(over.)

Fig. 17

Fig. 15

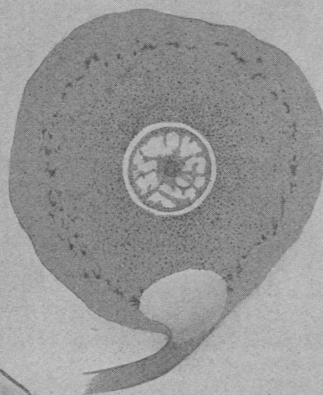


Fig. 19

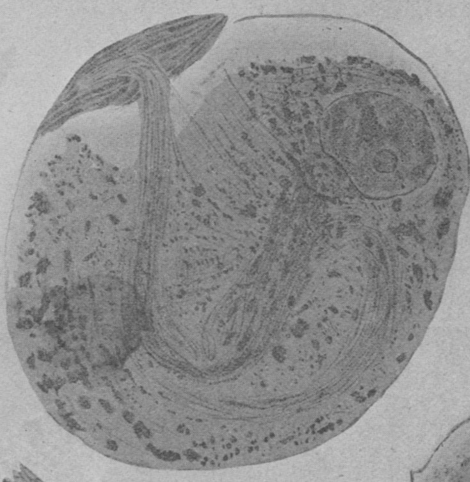
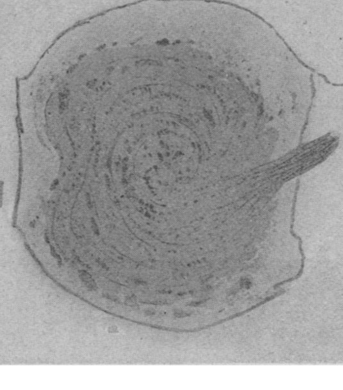


Fig. 20

Fig. 18



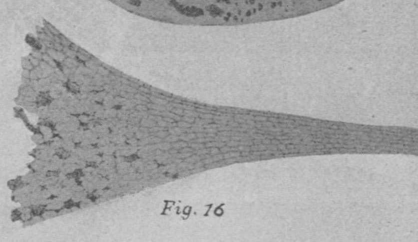


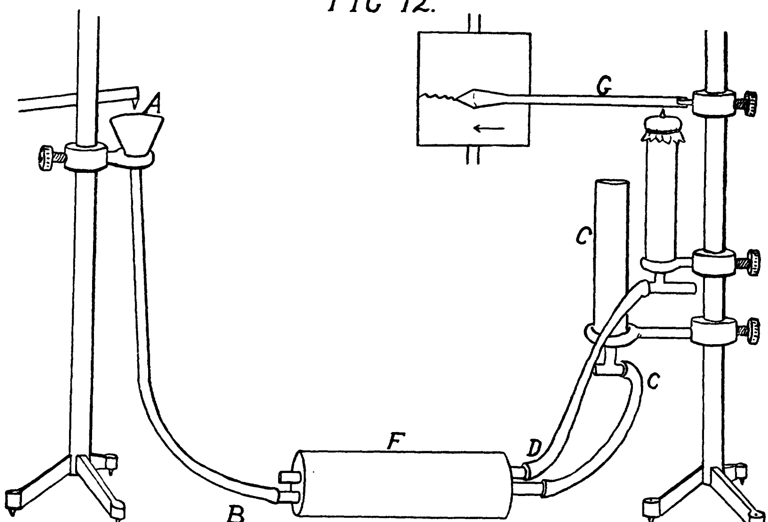
Fig. 16

duced different effects on the record *E*. Fig. 11a represents the results thus obtained.

FIFTH EXPERIMENT.

I tried to see the relation between the law of isolated conduction of stimulus and the paradoxical contraction; (Compare, I. Rosenthal, Allgemeine Physiologie der Muskeln und Nerven, 2te Aufl., S. 111 und 308). For this purpose I made the arrangement shown in Fig. 12. *B* is a rubber tube which

FIG 12.



is kept in contact with another tube *D*, by means of a larger tube *F*. *B* is excited at the end *A*, while the other end *C* is opened. A small amount of vibration was transmitted to the tube *D*, which was recorded by means of the recorder *G*, as is shown in the first half of Fig. 12a. When I pressed the tube *B* at a point between *F* and *C* to close the tube at C, the wave in the recorder became larger as is shown in the last half of the figure. It made no difference whether I gave the stimulus at *C* and closed the end *A*, while the other things remained the same. I may compare the case where *C* is opened to that of isolated conduction, while the other case where it is closed to the paradoxical contraction. For in the latter case a branch

of the nerve is cut off and thus the opening of the cut end must have been closed by the contraction of the protoplasm.

CONCLUSIONS.

The nervous system consists of nerve cells and fibers. The developmental unit of the system which comprises ganglion cell, neuraxon, dendrites, and their ramifications, is called a *neuron*. The neuraxon is an efferent cell-process, while dendrites are afferent processes. The aggregation of these units is held together by a network of fine fibrils called neuroglia.

If we take out one of the nerve cells and examine its interior structure, we find two constituents in it, structural and non-structural (Fig. 15). The former is called the cell-corpuscles of Nissl. The smaller corpuscles take the form of granules or fibers, while the larger ones, comparatively, are spindle, cone, or hood-shaped. These shapes differ in different cells. Thus different types of cells are formed. Nissl divides cells in the central nervous system into two classes. The first comprises those cells whose cell bodies are large and distinctly marked, and whose nuclei are entirely surrounded. These are called "somatochrome cells." The second comprises those whose cell bodies are small and are mostly occupied by a nucleus. Most of the nerve cells belong to the first class, which is again divided into the four following subclasses: the types of net-formed arrangement, that of striated arrangement, that of net-formed striated arrangement, and that of granulated arrangement. Recently, however, he has given the following division as a better one.

(1). A group of striated arrangement.

(2). A group of granulated arrangement.

(3). A group of those cells which resemble one another and are not comprised in any of those yet enumerated.

(4). A group of net-formed arrangement, which is to be divided into many subclasses.

There is a question as to whether the cell-corpuscles of Nissl are a natural structure, or a product of chemical treatment or other changes occurring in it after death. Held thinks that it is produced after death, for it does not appear in a cell immediately after death. Lenhossék thinks, however, that it is not

necessarily produced after death, for it appears in a fresh cell, at least, of the spinal ganglion. According to Marinesco, Nissl's corpuscle is an original formation, and is a source of energy. For this reason he calls it *Kinetoplasma*. Thus we see that there is as yet no definite idea concerning Nissl's corpuscle.

Moreover, we have a very imperfect idea concerning the nonstructural substance in the cell. This substance receives various names from different points of view. It is sometimes called intermediate substance, achromatic substance, ground substance, or ground mass (Held) of nerve-cell protoplasm, and sometimes it is called spongioplasm from its fine mesh constitution. *Nonstructural* is not a proper name, for recently its structure has been made visible. Lenhossék, however, discovered that the mesh-like appearance is due not to a net work of fine fibrils, but to an aggregation of fine granules. Bütschli and Held, on the other hand, affirm that this appearance is due partly to an aggregation of fine vacuoles which is very likely a result of chemical treatment, and partly to chains of fine granules which lie in the vacuoles (Fig. 16 and 17). They think that these structures are not limited in the cell body but continue to dendrons and axis cylinders. These items of information concerning the anatomy of nerve cells are taken from a work of Goldscheider and Flatau (A. Goldscheider und E. Flatau, Normale und pathologische Anatomie der Nervenzellen.)

According to Bühler, the fibriform structure of the axis cylinder takes a winding course, as is shown in Fig. 18. Sometimes the other end comes back to its point of original entry as is shown in Fig. 19. Or sometimes it enters at one place and goes out at another as is shown in Fig. 20. (Dr. med. Anton Bühler, Untersuchungen über den Bau der Nervenzellen.)

I tried an experiment to see whether I could produce such a winding appearance mechanically by means of an hydraulic wave. I took a properly shaped glass tube and connected it with a rubber tube which ended in a metallic funnel covered with a rubber sheet for receiving a series of strokes. I filled the whole tube with glycerine in which were short pieces of silk thread. Then I produced a series of waves in succession.

The threads in the glycerine took a winding shape in the glass tube.

Lastly, in regard to the question whether a nerve cell undergoes any mechanical change when an impulse passes through it, we have not any decided knowledge. The investigations of many scientists seem to show us that the activity of the nerve cell is accompanied by an increase of volume of the cell body, and a decrease of the chromatic constituent (Goldscheider und Flatau, *op. cit.*, S. 35).

The facts above described do not as yet answer the question of nervous conduction. Scientists of the present day think that nervous conduction is due to a chemical action caused by an organic function. But we do not know the details of the manner of the chemical action. Thus there is a possibility of trying some explantion other than chemical. For this reason I propose an hydraulic explanation. It supposes that nervous conduction is a transmission of a water wave in a protoplasmic tube and that the protoplasmic tube not only helps the transmission by its own elasticity but is excitable at any point by means of a stimulus directly applied to it. The wave is, of course, equally transmitted in both directions. Moreover this theory does not necessarily require a continuity of the path of conduction. Mere contact of tubes is enough to transmit a stimulus (compare the Fifth Experiment). Mere presence of the watery medium between two tubes is likewise enough for the purpose. The explanation has, however, its own difficulties. We cannot tell whether a nerve fiber is a sort of tube of protoplasm filled with a fluid or semi-fluid. If it is true that the fibrous appearance in the axis cylinder is a post-mortem product, we cannot infer anything from this as to the nature of protoplasm in life. I am not ready to explain everything on the hydraulic principle. If the water wave is to explain nervous conduction, it must be supplemented by the contraction of protoplasm, which forms the tube, to account for excitability. As to further information on the nature of conduction, we must wait for future discovery.

There are two large classes of psychical phenomena which are very conveniently explained under the supposition of a protoplasmic tube. They are the phenomena of attention and

inhibition. According to our hypothesis, these two phenomena are looked upon as two aspects of one and the same phenomenon. Attention is one aspect of an activity where impulses centralize, while inhibition is the other where impulses are turned away. If there is attention in one place, there must be inhibition in another. If any part of the brain becomes active, the nerve cells and fibers of that part, increase in volume, and impulses are gathered there in consequence; this coincides with a result of our investigation. In other words, impulses come together, and focus at a point where activities already exist. Thus they keep their attentive state until the cells and fibers of that part become tired, when the attention passes to another point.

In regard to the nature of inhibition I have not as yet a decided opinion. It would be proper, however, to distinguish two kinds of inhibition. (1). There is, so to speak, an inertia of the nerve, that is, it needs to heap up some energy before it is called into activity. The energy, thus spent, can be said to have been inhibited. For this reason, when a nerve cell is in a state of activity, it transmits a comparatively small amount of the energy newly arrived. (2). By hypothetically accepting the contraction of neuroplasm when stimulated, and, as its consequence, a little widening of the nerve fiber, we may affirm that those cells together with dendrites and fibers, which are already in a state of activity, have less resistance to the conduction of a stimulus than those at rest. If this affirmation is correct, a stimulus coming from the periphery to a center would be led off toward such a part as is already in the state of activity. Thus when a star-fish put upside down tries to recover its proper position by means of one of its legs helped by a few neighboring ones while the other legs are at rest, it accomplishes its purpose. Some legs seem to be at rest as a consequence of the concentration of the excitation in the other legs. Therefore, if the central connection of the nerves were cut, all the legs would act simultaneously. Again when we direct our attention earnestly to a special point, and therefore only one part of our brain is in a state of activity, the other parts are almost insensible to a stimulus. Thus we try to depress the sensation of pain in surgical operations by turning

attention somewhere else. The inhibitory influence of the vagus on the heart may be considered as a consequence of its expansion caused by a stimulus, and of its leading away the stimuli originated in the heart itself. In these cases, the stimulus is led off toward the point which is active. This is not really inhibition, but only turning off the stimulus.

In the reflex action of a frog whose brain has been cut off, when one leg is stimulated, that leg is moved. When the intensity of stimulus is increased, the other leg is moved, and by increasing it still further, the arm on the same side is moved, and so on. These facts seem to coincide with our experiment, on the relation of the length of tube to wave conduction.

Finally, I might say that a chemical action may explain these phenomena just as well as an hydraulic principle. But, in that case, the former must work according to the same law as the latter, for attention and inhibition are sufficiently explicable under the hydraulic supposition. As to the special application of this principle to psychology, I must defer what I have to say to a future work.